

# Cassini Maneuver Experience Through the Final Targeted Titan Flyby and the Grand Finale

**Sean Wagner**

**Yungsun Hahn, Sonia Hernandez, Frank Laipert,  
Powtawche Valerino, Mar Vaquero, and Mau Wong**

**AAS/AIAA Astrodynamics Specialist Conference**

**Stevenson, Washington**

**August 20-24, 2017**

**AAS 17-596**

**URS267723 – Cleared for Unlimited Release – CL#17-4014**

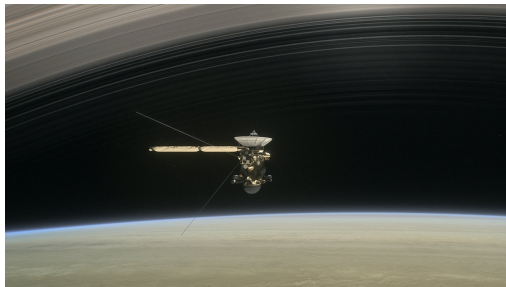
**© 2017 California Institute of Technology. U.S. Government sponsorship acknowledged.**

# Cassini Mission at Saturn and Titan / Grand Finale

The Cassini-Huygens spacecraft launched on October 15, 1997. After a seven-year cruise, it arrived at Saturn on July 1, 2004 and began a four-year Prime Mission to study the Saturnian system.

Two extended missions followed:

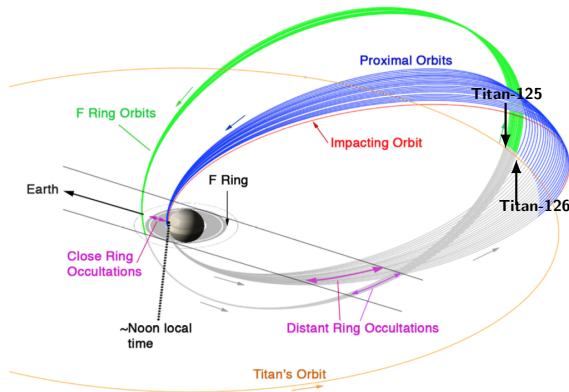
- Equinox Mission in September 2008 (2+ years)
- Solstice Mission in September 2010 (7 years)



## The Cassini Grand Finale

- Began April 22, 2017 and ends when Cassini plunges into Saturn's atmosphere on September 15, 2017
- Unique opportunity to study Saturn from within a 2,550 km wide gap between Saturn's cloud-tops and inner-most D-ring

# Cassini Grand Finale



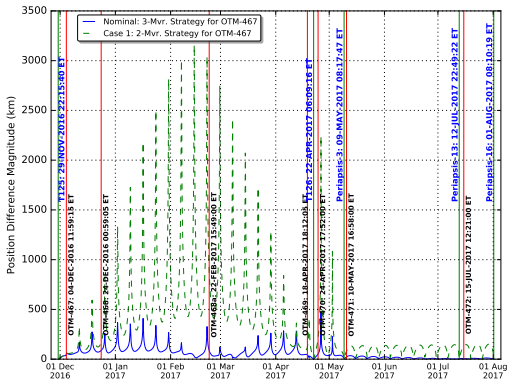
- F-Ring Orbits:**  
 20 Saturn revs (7 day period) from November 2016 to April 2017
- Proximal Orbits (Grand Finale):**  
 22 Saturn revs (6.5 day period) from April to September 2017

- Seven maneuvers performed from December 2016 to July 2017:
  - OTMs 467, 468, 468a, & 469: targeted last Titan flyby (T126)
  - OTMs 470, 471, & 472: targeted proximal orbit periapses P-3, P-13, and P-16

# OTM-467 (December 4, 2016)

OTM-467, cleanup to previous Titan flyby (T125) and targeting maneuver to T126

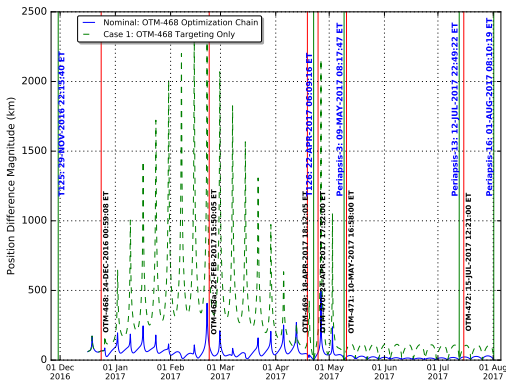
- Last main engine burn (Design  $\Delta V = 0.994$  m/s)
- Designed in an optimization chain with next two maneuvers targeting T126: OTM-468 & OTM-468a
- If chained with only OTM-468a, downstream  $\Delta V$  cost of 0.4 m/s & trajectory deviations increase from 500 km to 3000 km prior to T126



# OTM-468 (December 24, 2016)

OTM-468, second maneuver to target T126

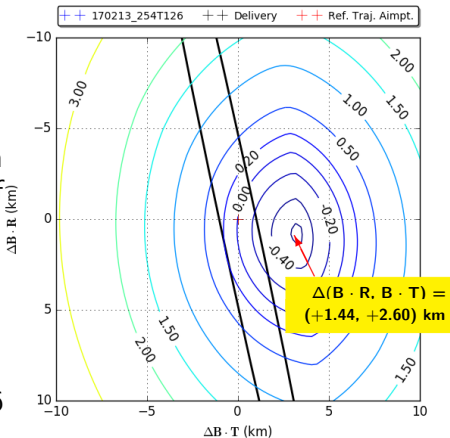
- Large RCS burn (Design  $\Delta V = 0.227$  m/s)
- Designed in an optimization chain with OTM-468a to target T126
- If not designed with OTM-468a, downstream  $\Delta V$  cost of 0.4 m/s & trajectory deviations grow to nearly 2500 km prior to T126



# OTM-468a (February 22, 2017)

OTM-468a, third maneuver to target T126

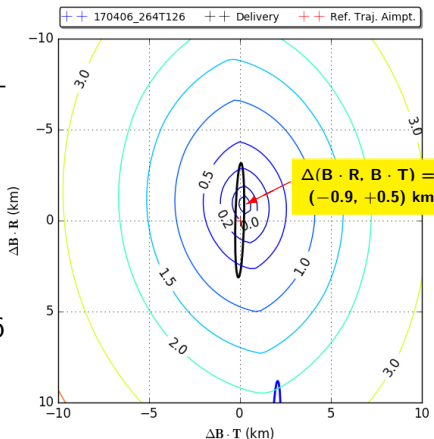
- Large RCS burn (Design  $\Delta V = 0.196$  m/s)
- Statistical maneuver added after Solstice Mission began to reduce predicted mean of OTM-469
- Backup maneuver added 1.1 m/s cost
- However, changing target for backup removed half of the cost and changing T126 TCA by 10 sec removed rest of cost



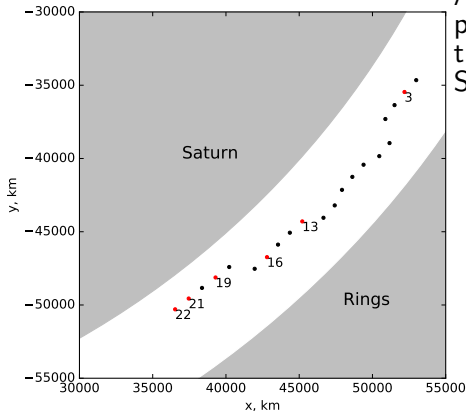
# OTM-469 (April 18, 2017)

OTM-469, final approach maneuver to T126

- Small RCS burn (Design  $\Delta V = 0.059$  m/s)
- Small aimpoint change saved 167 mm/s in projected downstream  $\Delta V$  cost and reduced post-T126 trajectory deviations



# Ring Plane Crossings at Periapsis



After T126 on April 22, 2017, Cassini placed in 6.5 day orbit passing 22 times through gap between inner D-ring and Saturn atmosphere

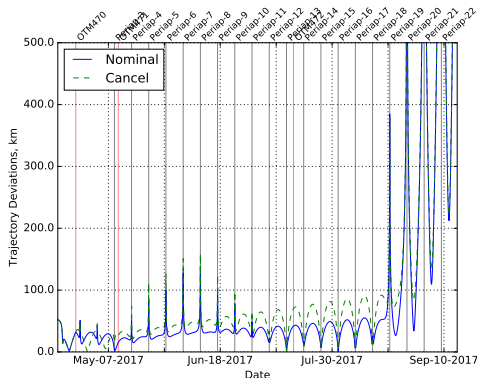
- Initially, all trajectory deviations at 22 periapses were desired to be under 250 km
- Project later decided only trajectory deviations at P-3, P-14, and P-16 were required to be under 250 km
- Navigation developed a 3-mvr. control strategy to target P-3, P-13, and P-16 via OTMs 470, 471, & 472 (ref. traj. XYZ+2 hours)



# OTM-470 (April 24, 2017)

## OTM-470, target P-3

- Mid-sized RCS burn  
(Design  $\Delta V = 0.156$  m/s)
- Performing OTM-470 at prime or backup, or cancelling maneuver, yielded similar downstream  $\Delta V$  costs and trajectory deviations
- Since OTM-471 was still required for targeting P-13, OTM-470 was performed to reduce growth of OTM-471

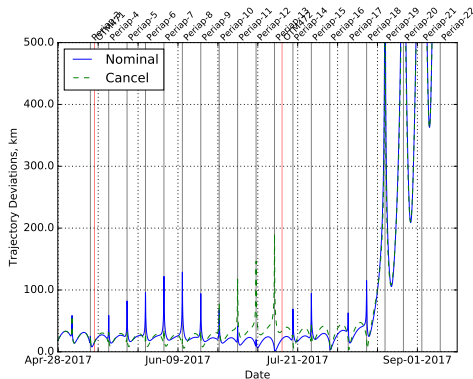


Target	Maneuver	$\Delta V$ (m/s)
P-3	OTM-470	0.156
P-13	OTM-471	0.043
P-16	OTM-472	0.021
Total $\Delta V$		0.220

# OTM-471 (May 10, 2017)

## OTM-471, target P-13

- Small RCS burn (Design  $\Delta V = 0.020$  m/s)
- Like OTM-470, performing OTM-471 at prime or backup, or cancelling maneuver, yielded similar downstream  $\Delta V$  costs
- However, trajectory deviations at P-13 would grow near 250 km limit if cancel OTM-471
- Same argument as OTM-470: OTM-471 was performed to reduce growth of OTM-472



Target	Maneuver	$\Delta V$ (m/s)
P-13	OTM-471	0.020
P-16	OTM-472	0.056
Total $\Delta V$		0.076

# OTM-472 (July 15, 2017)

## OTM-472, target P-16

- Mid-sized RCS burn (Design  $\Delta V = 0.145$  m/s)
- Without OTM-472, all periapses beginning with P-14 would be well above 250 km deviation requirement
- A few notes about OTM-472
  - Predictions of small force  $\Delta V$ s after OTM-472 were not available until after OTM-471
  - After P-3 on May 9, 2017, OD team began observing a very small “drag-like” effect which caused periapsis times to consistently drift earlier
    - Caused OTM-472 to grow as well as deviations
    - Effect disappeared after P-11 on June 29, 2017

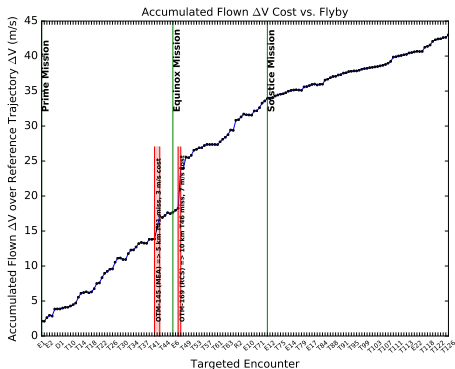
MAPDF ID	OD Solution	$\Delta V$ Mag. (m/s)
O472.x	170510.271GF	0.0463
O472.x	170515.271GF	0.0393
O472.x	170516.271GF	0.0593
O472.x	170518.271GF	0.0473
O472.x	170522.271GF	0.0578
O472.x	170525.271GF	0.0610
O472.x	170530.271GF	0.0915
O472.x	170601.276GF	0.0899
O472.x	170604.276GF	0.0949
O472.x	170608.276GF	0.1000
O472.x	170611.276GF	0.1157
O472.x	170616.1.276GF	0.1153
O472.x	170619.276GF	0.1319
O472.x	170622.276GF	0.1320
O472.x	170626.276GF	0.1524
O472.d	170630.281GF	0.1504
O472.d	170705.281GF	0.1494
O472.d	170706.281GF	0.1435
O472.d	170710.281GF	0.1448
O472.d	170712.281GF	0.1447

## Pop-Up / Pop-Down Contingency Maneuvers

- For the last five revolutions in the Grand Finale, Cassini will fly lower than ever before in Saturn's atmosphere
- Atmosphere will be assessed by Cassini mission planners at each ring plane crossing using thruster duty cycle data to determine if a "pop-up" to raise periapsis or "pop-down" to lower periapsis will be needed
- One or more of the following three maneuvers may be performed in the weeks prior to Cassini's plunge into Saturn on September 15, 2017:
  - OTM-473, a "pop-up" maneuver (for spacecraft health and safety reasons) scheduled for August 17, 2017 and targeted to P-19
  - OTM-474, a "pop-down" maneuver planned for August 30, 2017 and targeted to P-21
  - OTM-475, a "pop-down" maneuver scheduled for September 5, 2017 and targeted to P-22

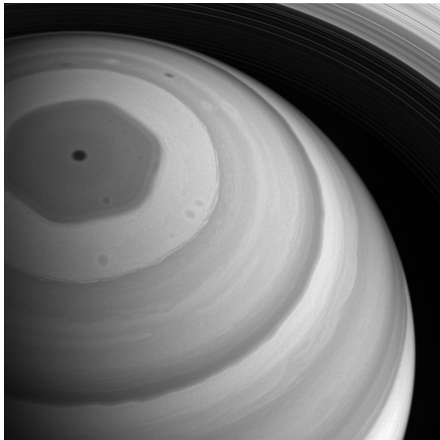
# Navigation Performance

Mission	Flyby Span	Number of Flybys	Navigation $\Delta V$ Cost	
			Mean (m/s)	Std. Dev. (m/s)
Prime (7/2004 – 9/2008)	Ta – E4	54	0.325	0.594
Equinox (9/2008 – 9/2010)	E5 – T72	36	0.447	0.978
Solstice (9/2010 – 4/2017)	T73 – T126	70	0.135	0.146

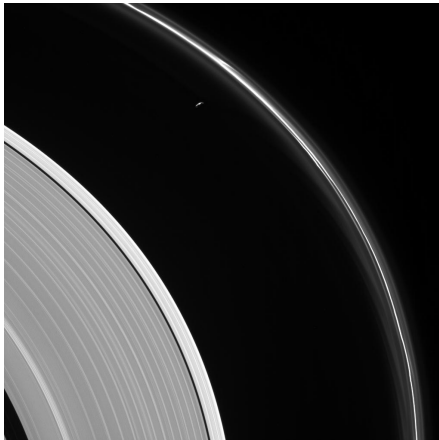


- Navigation cost (flown vs. planned  $\Delta V$ ) was only 43 m/s for entire mission
- Stellar maneuver performance during Saturn tour w/ only two exceptions:
  - OTM-145, large MEA approach maneuver: 5 km Titan-41 miss and 3 m/s cost
  - OTM-169, large RCS approach maneuver: 10 km Titan-46 miss and 7 m/s cost

## Some Recent Cassini Mission Highlights

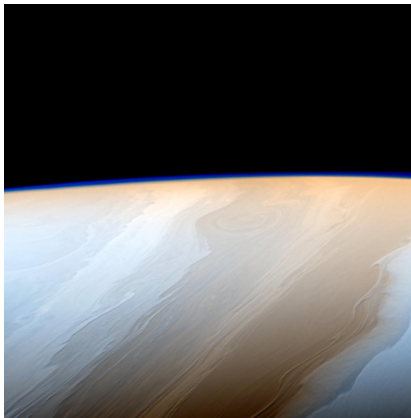


*Saturn's North Pole Basking in Light (Sept. 9, 2016)*

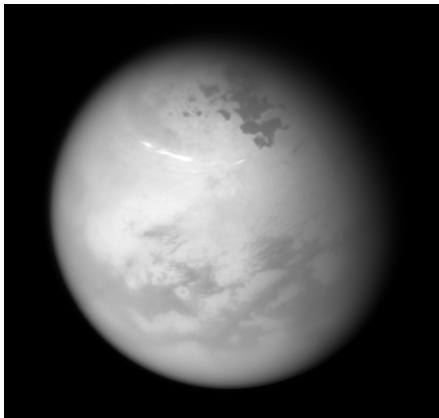


*Prometheus and the Ghostly F Ring (May 13, 2017)*

## Some Recent Cassini Mission Highlights



*Saturn's Cloudy Waves, False Color (May 18, 2017)*



*Northern Summer on Titan (June 9, 2017)*

# Conclusion

- Much of the success of Cassini through launch, interplanetary cruise, Saturn tour, and the Grand Finale can be attributed to the excellent performance of maneuvers designed by the Cassini Navigation Team
  - Over 500 maneuvers planned and exactly 360 maneuvers performed
  - A total of 160 flybys of Titan, Enceladus, and several of the icy moons successfully targeted by Navigation
- The Grand Finale presented a unique opportunity for scientists to study Saturn from within a 2,550 km wide gap between Saturn's cloud-tops and the inner-most D-ring
  - Saturn's internal structure (gravity and magnetic fields)
  - Ring mass and age of main rings
  - In-situ measurements of the ionosphere, inner radiation belts, D-ring particles, etc.
- Mission ends when Cassini plunges into Saturn's atmosphere on September 15, 2017, but many years ahead to study all the science the mission has yielded about the Saturnian system